Effect of Oil Injection into the Cylinder of a Gas Engine

A. W. Mac Millan
Benjamin Natkin
F. R. Goldsmith

1 9 0 5

621.4
M 22

ARMOUR
INST. OF TECH. LIB.
CHICAGO.

Illinois Institute
of Technology
Libraries

AT 15
MacMillan, Arthur W.
The effect of oil injection
into the cylinder of a gas

732
84 a

THE

EFFECT OF OIL INJECTION INTO THE CYLINDER OF A GAS ENGINE.

A THESIS PRESENTED
BY

Arthur W. MacMillan
Benjamin Natkin
Frank R. Goldsmith

to the

PRESIDENT and FACULTY
of the

ARMOUR INSTITUTE OF TECHNOLOGY

for the degree of

BACHELOR OF SCIENCE
in
MECHANICAL ENGINEERENG

Having completed the required course of study in

MECHANICAL ENGINEERING

CHICAGO, JUNE 15, 1905

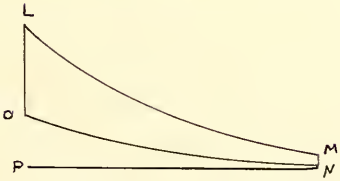
ILLINOIS INSTITUTE OF TECHNOLOGY
PAUL V. GALVIN LIBRARY
35 WEST 33RD STREET
CHICAGO, IL 60616

Approved
G. F. Gebhardt

EFFECT OF OIL INJECTION INTO THE CYLINDER OF A GAS ENGINE.

The rapid increase in the application of the gas engine as a prime-mover stimulates scientific investigation with the object of overcoming some of its most prominent defects, namely, its uneven crank effort, and the inflexibility of its working diagram, which but imperfectly adapts itself to the resistance offered.

The majority of gas engines at the present time work under the Otto cycle: drawing in the charge during the first stroke, compressing this charge during the second stroke, at the end of which, explosion takes place. Expansion of the products of combustion, (approximately adiabatic), produces the crank-effort during the third stroke. The fourth stroke cleanses the cylinder of the spent gases. The crank effort is produced by a sudden blow when the crank is near the dead center; the pressure rising instantaneously and dropping almost immediately. From the thermodynamic stand point, this cycle is analyzed as follows;-



From N to O the gas is compressed adiabatically from armospheric p pressure.

From O to L the gas receives heat isometrically.

From L to M the gas is expanded adiabatically to some value above the atmospheric.

From M to N the gas is cooled isometrically to atmospheric pressure.

17977

Let the heat added from 0 to L = H_1

Let the heat rejected from M to N = H_2

then $H_1 = (T_L-T_0)C_v$

$H_2 = (T_M-T_N)C_v$

the efficiency, $e = \frac{H_1-H_2}{H}$

or
$$e = \frac{C_v(T_L-T_o)-C_v(T_M-T_N)}{C_v(T_L-T_o)}$$

which reduces to the equation

$$e = 1-\frac{T_M-T_N}{T_L-T_o}$$

but
$$T_M V_M^{K-1} = T_L V_L^{K-1}$$

and
$$T_N V_N^{K-1} = T_o V_o^{K-1}$$

therefore
$$\frac{T_M}{T_N} = \frac{T_L}{T_o}$$

then
$$\frac{T_M-T_N}{T_L-T_o} = \frac{T_M}{T_L} = \frac{T_N}{T_o} = \left(\frac{V_o}{V_N}\right)^{K-1}$$

whence
$$\epsilon = 1-\left(\frac{V_o}{V_N}\right)^{K-1}$$

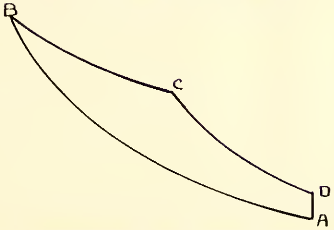
The value of K for a mixture of 8:1 is approximately 1.37 This equation shows that the efficiency is dependent only on the compression.

As previously stated, this cycle, although efficient from the thermodynamic standpoint, does not allow uniform crank-effort, or flexibility in its working diagram. In the steam engine, these qualities are obtained by a period of constant pressure before the expansion. The length of this constant pressure period may be varied to suit the conditions. The result is that a nice degree of government is obtainable, allowing alternators on separate engines to be run in synchronism. At present this is not obtainable in the gas engine. Although the uncertainty of the propagation of the flame is one drawback, this is subordinated to the undesirable distribution of energy in the cycle.

The principles which suggest themselves as offering possible

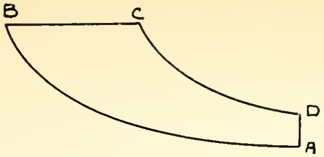
remedies may be found in the modern Diesel Engine, and in the old Brayton Engine in 1860.

The Diesel Engine uses oil which is forced into the cylinder by a small oil pump. The first stroke of the engine draws in air only; the second stroke compresses this air to the enormous pressure of 500 lbs. per square inch. This compression heats the air to such a point that the oil injected burns, producing a constant temperature expansion for a short period, till the oil supply is cut off, when the products of combustion expand, approaching the adiabatic line. The cycle is as follows;-



From A to B adiabatic compression from atmospheric pressure.
From B to C addition of heat isothermally.
From C to D adiabatic expansion to pressure above atmospheric.
From D to A cooling isometrically to atmospheric pressure.

The Brayton engine has two cylinders, one a compressing pump and the other the motor. They are of the same diameter. The stroke of the pump is half that of the motor cylinder. The pump compresses the mixture to a pressure between 60 and 80 pounds per square inch. The motor cylinder takes its supply from an intermediate receiver. The mixture itself never enters the motor cylinder. What does enter is a large flame. A grating prevents this flame from passing back. By suitable valves, this flame is increased and diminished. The products of combustion are expanded in the motor independent of the receiver. The result is a constant pressure line before the adiabatic expansion. The cycle is as follows:-



From A to B adiabatic compression from atmospheric pressure.

From B to C addition of heat isopiestically.

From C to D adiabatic expansion to pressure above atmosphere.

From D to A cooling isometrically to atmospheric.

Although little power is developed in a reasonable size of this type of engine, and considerable difficulty is experienced with clogging, the engine has the distinct advantage of uniform and easily controllable crank effort.

After a thorough investigation in the comparison of these three cycles,# Hutton concludes that if the mass of gas, heat supplied and compression is the same for the three cycles mentioned, namely, the Otto, Diesel and Brayton, the same work will be done and consequently the same efficiency will be obtained. He has also found the following conditions to be true:-

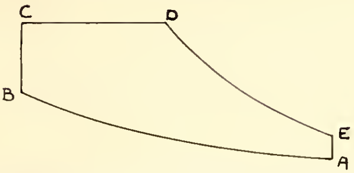
	Lowest	Intermediate	Highest
Maximum temperature	Carnot	Brayton	Otto
Pressure range	Brayton	Carnot	Otto
Volume range	Otto	Brayton	Carnot
Temperature range	Carnot	Brayton	Otto
M.E.P.	Carnot	Brayton	Otto
Pressure range÷M.E.P.	Brayton	Carnot	Otto

It may be seen according to the above table that either the Brayton or Otto cycles have that degree of quality which is most desirable. For example, a low volume range is desirable: the Otto cycle has this quality: the temperature range of the Brayton is only exceeded by the Carnot. The maximum temperature of the Brayton is the lowest, while the Otto has the highest M.E.P., a quality which is very desirable.

These results suggest additional reasons why a combination

See Hutton's "The Gas Engine," p. 405 ff.

of the Brayton and the Otto cycles would be desirable. The combined cycle would be as follows:-



From A to B adiabatic compression from atmospheric pressure.

From B toC addition of heat isometrically.

From C to D addition of heat isopiestically.

From D to E adiabatic expansion to pressure above atmosphere.

From E to A cooling isometrically to atmospheric pressure.

From the thermodynamic standpoint this cycle is analyzed as follows:-

Let p_a, p_b, p_c,etc.= absolute pressure at A, B, C,etc.

v_a, v_b, v_c,etc,= volumes at A,B,C,etc.

T_a, T_b, T_c,etc.= absolute temperatures at A,B,C,etc.

Since the mixture in the engine is to be considered as a "perfect" gas, it will be well to give the fundamental laws governing such gases.

1. Boyle's Law.- The product of volume and temperature remain constant as long as the temperature is constant.

$$p_1 v_1 = p_2 v_2 = \text{conatant.}$$

2. Gay-Lussac's Law.- At constant pressures, the absolute temperatures are proportional to the volumes.

3. Combination of both laws:-

$$\frac{P V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

Each event of the cycle will now be considered, and its conditions in regard to pressure. volume and temperature determined.

At the beginning of the cycle A

v_a= volume of cylinder and clearance

p_a = atmospheric pressure.

T_a = room temperature plus 461° F.

From A toB we have adiabatic compression, after which

v_b = cleanance volume

$$P_b = P_a\left(\frac{V_a}{V_b}\right)^K$$

and $$T_b = T_a\left(\frac{V_a}{V_b}\right)^{K-1}$$

where K is the ratio of the specific heats of the mixture, and equals about 1.37

From B to C an amount of heat H_1 is added isometrically and since the volume remains constant, we have from Gay-Lussacs Law

$$P_c = P_b\frac{T_c}{T_b}$$

The increase in temperature from B to C is

$$T_c - T_b = \frac{H_1}{C_v}$$

$$\therefore\ T_c = \frac{H_1}{C_v} + T_b = \frac{H_1}{C_v} + T_a\left(\frac{V_a}{V_b}\right)^{K-1}$$

where c_v is the specific heat at constant volume.

From C to D an amount of heat equal to H_2 is added isopiestically.

The rise in temperature is

$$T_d - T_c = \frac{H_2}{C_p}$$

where c_p is the specific heat at constant pressure. The temperature at T_d is therefore

$$T_d = T_c + \frac{H_2}{C_p} = \frac{H_1}{C_v} + T_a\left(\frac{V_a}{V_b}\right)^{K-1} + \frac{H_2}{C_p}$$

$$= H_1\frac{C_p}{C_v} + T_a\,C_p\left(\frac{V_a}{V_b}\right)^{K-1} + H_2$$

$$= \frac{H_1 K}{C_p} + T_a\left(\frac{V_a}{V_b}\right)^{K-1} + \frac{H_2}{C_p}$$

$$P_d = P_c = P_b\frac{T_c}{T_b} = P_a\left(\frac{V_a}{V_b}\right)^K\frac{T_c}{T_b}$$

Since the pressure is constant, the volume will follow Gay-Lussac's Law

$$V_d = V_c\frac{T_d}{T_c} = V_b\frac{T_d}{T_c}$$

From D to E we have adiabatic expansion to some value above the atmosphere whose pressure will equal

$$P_e = P_d\left(\frac{V_d}{V_e}\right)^K = P_c\left(\frac{V_d}{V_e}\right)^K$$

$$P_e = P_b \frac{T_c}{T_b}\left(\frac{V_d}{V_e}\right)^{K}$$

But $v_d = v_a$

Therefore $P_e = P_b \frac{T_c}{T_b}\left(\frac{V_d}{V_a}\right)^{K}$

The temperature during an adiabatic expansion is

$$\frac{T_e}{T_d} = \left(\frac{P_e}{P_d}\right)^{\frac{K-1}{K}}$$

$$\therefore\ T_e = T_d\left(\frac{P_e}{P_d}\right)^{\frac{K-1}{K}} = T_d\left(\frac{V_d}{V_e}\right)^{K-1}$$

$$= \left(T_c + \frac{H_2}{c_p}\right)\left(\frac{V_d}{V_e}\right)^{K-1}$$

From E to A cooling occurs isometrically, and an amount of heat H_3 is abstracted when the gas is finally reduced to its initial condition

$$H_3 = c_v(T_e - T_a)$$

$$= c_v\left(T_c + \frac{H_2}{c_p}\right)\left(\frac{V_d}{V_e}\right)^{K-1} - T_a$$

$$= c_v\left[\frac{H_1}{c_v} + T_a\left(\frac{V_a}{V_b}\right)^{K-1} + \frac{H_2}{c_p}\right]\left(\frac{V_d}{V_e}\right)^{K-1} - T_a$$

$$= \left[H_1 + T_a c_v\left(\frac{V_a}{V_b}\right)^{K-1} + \frac{H_2}{K}\right]\left(\frac{V_d}{V_e}\right)^{K-1} - T_a$$

The amount of heat converted into work in this cycle is the difference between the amount of heat supplied and the heat rejected and the work equivalent is then equal to

$$W = J(H_1+H_2-H_3)$$

$$= J(H_1+H_2-C_v(T_e-T_a))$$

The thermal efficiency is the amount of heat converted into work divided by the heat put in.

$$\text{eff} = \frac{H_1+H_2-H_3}{H_1+H_2} = \frac{H_1+H_2-C_v(T_e-T_a)}{H_1+H_2}$$

But $H_1 = c_v(T_c-T_b)$

$H_2 = c_p(T_d-T_c)$

$$\text{Therefore eff.} = \frac{c_v(T_c-T_b) - c_v(T_e-T_a) + c_p(T_d-T_c)}{c_v(T_c-T_b) + c_p(T_d-T_c)}$$

Substituting K for $\frac{c_p}{c_v}$

and $\frac{T_e}{T_b}$ for $\left(\frac{V_B}{V_c}\right)^{K-1}$

$$\frac{T_b}{T_a} \text{ for } \left(\frac{V_a}{V_b}\right)^{K-1}$$

$$\frac{T_d}{T_c} \text{ for } \left(\frac{V_c}{V_d}\right)^{K-1}$$

the equation finally reduces to

$$\text{eff} = 1-\left(\frac{V_b}{V_a}\right)^{K-1}$$

It may be noted that the value of the efficiency of this new cycle is of the same form as the Otto cycle; depending entirely upon the compression curve.

Three possible methods for obtaining an approximation of this cycle presented themselves-:

1. Injection of gas and air into the cylinder immediately after explosion.

2. Pumping of oil, in small quantities, and air directly into the cylinder immediately after explosion of the gas mixture.

3. Forcing oil and air into the cylinder in proper quantities and intervals by pneumatic pressure.

The first and second methods were abandoned as they involved the construction of apparatus prohibitive in the available time. The third method was adopted because of the simplicity of apparatus required, most of which was at hand. The uncertain quantity was the pump which was to supply and maintain the pressure.

Before constructing the apparatus allowing the injection of oil, the probable quantity which must be used per stroke must be estimated. As a preliminary estimation, this quantity was calculated on the heat basis, allowing sufficient oil to increase the original card by one half. The following data upon which the calculations were based was obtained from the 7 H.P. Fairbanks Gas Engine to be used. These quantities are the result of a four hour run with illuminating gas.

Gas consumed per hour,(30" Hg.,62°)	166.15 cu.ft.
Heating value of gas,	600 B.T.U. per cu.ft.

Explosions per minute 104.

The total B.T.U. consumed per hour is

$$600 \times 166.15 = 99700 \text{ B.T.U.}$$

The B.T.U. per explosion is therefore

$$\frac{99700}{60\text{x}104} = 17.2$$

To increase the card by one half, assuming no change in efficiency requires the addition of 8.6 B.T.U. per explosion, or 875 B.T.U. per minute. With a heating value of 1900 B.T.U. per pound at a specific gravity of .8 the amount of kerosene required per minute would be

$$\frac{895}{19000} = .047 \text{ lbs of kerosene per minute}$$

1 lb. of kerosene occupies 34.5 cu. in.
.047lbs. occupy 1.63 cu.in.
$\frac{.047}{104}$ " .015 cu.in.

In other words, the maximum quantity of oil used per explosion would be .015 cu. in. or .000154 gal.

The amount of air required for the complete and perfect combustion of the oil is calculated as follows with kerosene of 85% C and 12% H burning to CO_2

$$C + O_2 = CO_2$$

from the atomic weights 12 + 32 = 44

then 12 lbs. of carbon require 32 lbs. of oxygen
.85 lbs. require " 2.26lbs. " "

The hydrogen during combustion is converted into steam

$$H_2 + O = H_2O$$

from the atomic weights 2 + 16 = 18

then 2 lbs. of hydrogen require 16 lbs. of Oxygen
.12 " " " " $\frac{16}{2}$x.12 = .96 lbs.

Therefore 1 lb. of kerosene requires 2.26 + .96 or 3.22 lbs. of oxygen.

.23 of air is oxygen,

therefore $\frac{3.22}{.23}$ or 14 lbs. of air are required per lb. of oil.

1 lb. of air at 62°F and atmospheric pressure occupies 11.8cu.ft.

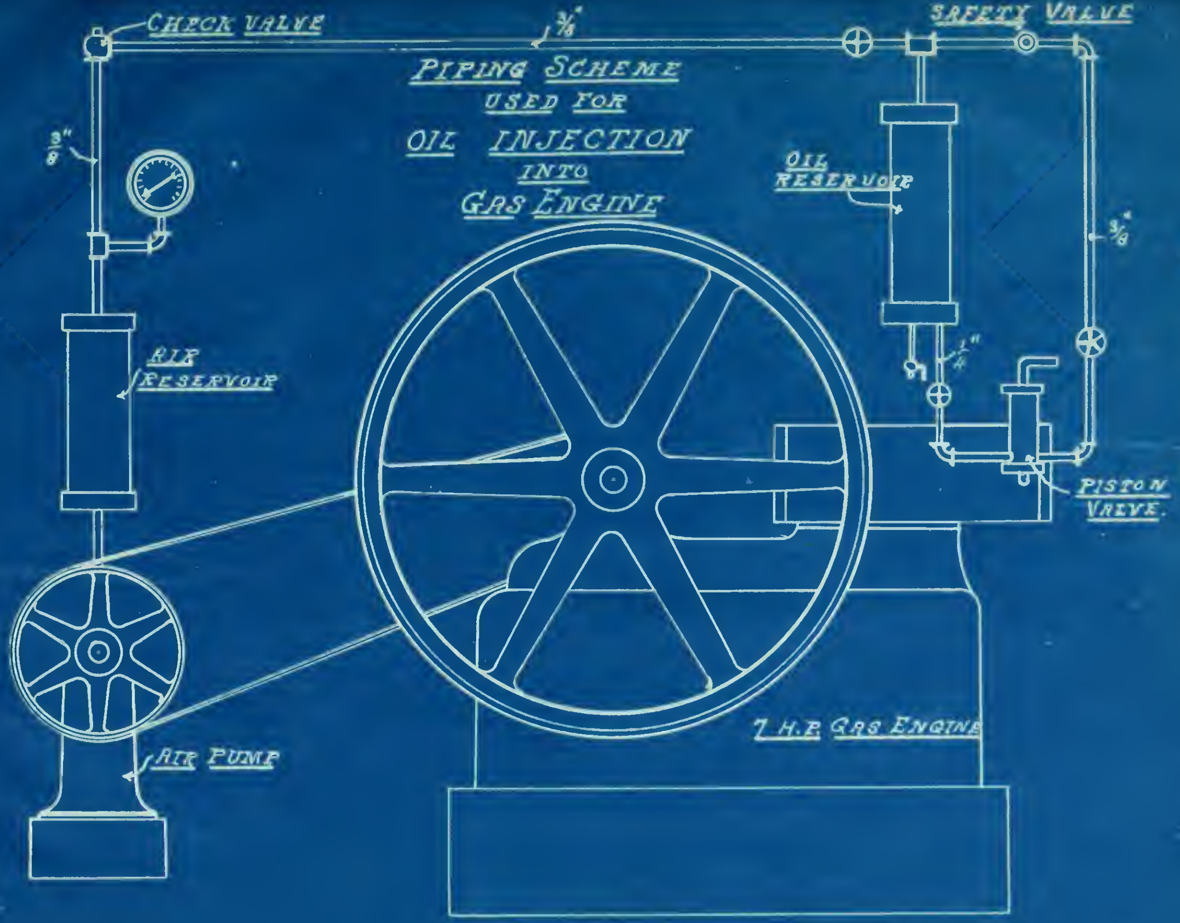
14 lbs occupy 14x11.8, or 165 cu.ft.

Thus .047 lbs. of kerosene require 165x.047, or 7.8 cu.ft. of air, the quantity required per minute for combustion of the oil.

Either of two engines could be used, a 40 H.P. 3 cycle Westinghouse, or a 6-3/4"x10", 7 H.P. horizontal Fairbanks Gas Engine. Due to its lower pressure of explosion, and the advantage of one cylinder, the latter was chosen. This engine has the "hit or miss" type of government. At the proper interval, the miss-fire is caused by the exhaust valve remaining open during the suction stroke. This allows the mixture inlet valve, actuated by the difference in pressure to remain closed. A water cooled brake pulley is keyed to the shaft. This is surrounded by a Prony brake, the arm of which rests upon suitable scales. Belted to the engine is a 3"x4" vertical single stage air compressor with a pulley 20" in diameter. The pulley of the angine is 13" in diameter. When the engine is running at its rated speed, 250 r.p.m., the pump revolves at 163 r.p.m.

The scheme adopted was to consume the least time in the construction of apparatus, and involved the pressure of explosion to operate a piston valve allowing oil and air under pressure to enter the cylinder. A spring above the valve regulated the duration of port opening and the quantity of oil used per stroke. As the actual card from the Diesel engine shows a cross between ab isothermal and a period of constant pressure during the addition of oil, it is reasonable to suppose there will be enough drop of pressure in our case to allow a nice regulation, by varying the initial tension of the spring. The entire valve arrangement, see Fig.(1), consists of a vertical cast iron cylinder with a 1" bore tapped to ——————

PIPING SCHEME USED FOR OIL INJECTION INTO GAS ENGINE

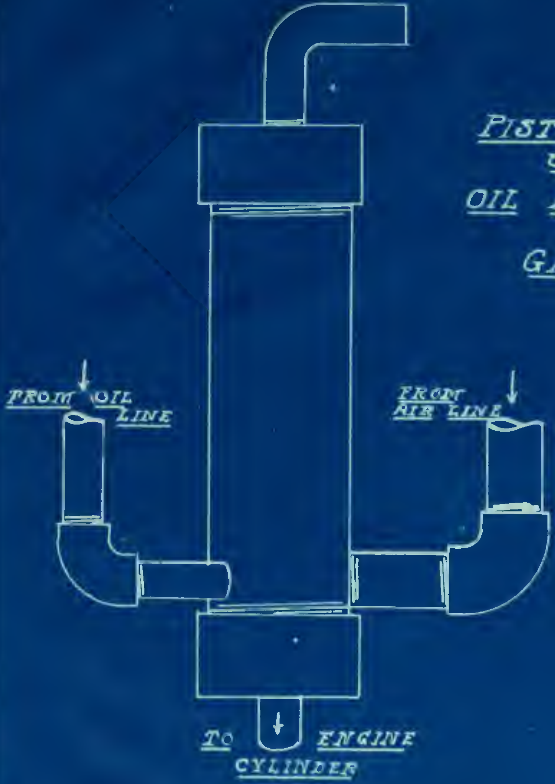


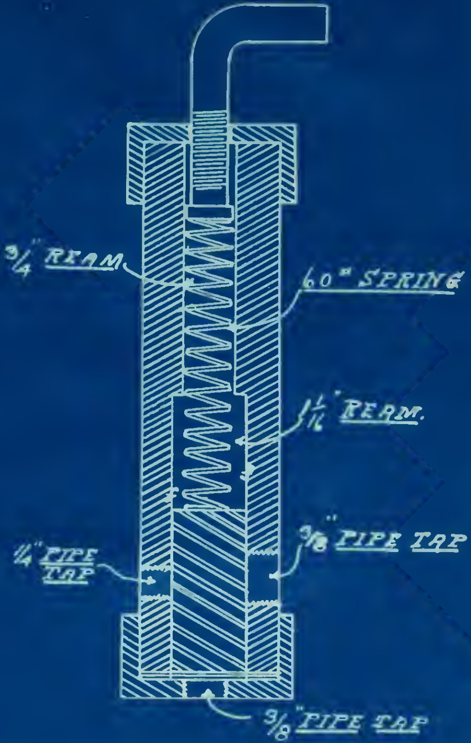
size. A tempered ground tool steel piston was made to allow an air tight sliding fit. As may be seen in the diagram, the cylinder is capped at both ends, the lower end tapped for the supply pipe for the oil and air to the cylinder. An iron mesh is placed at the bottom of the cap to spray the oil as it enters the cylinder. The upper cap is tapped for a 3/8" pipe, which is threaded for 4". This pipe serves to regulate the initial tension of the 60 pound spring and to allow a vent to the atmosphere for the air above the piston. A 1/4" oil pipe and a 3/8" air pipe enter this cylinder on the same level.

This arrangement worked perfectly, the piston working continuosly and smoothly, with very little leakage. This was accomplished, however, only after tempered tool steel was used in place of a number of wrought iron and cast iron pistons which stuck after a few moments use. The sticking in these cases was found to be due to a slight enlargement at the end coming in contact with the stop. No difficulty whatever was experienced with the valve when the piston was made of tool steel. The whole arrangement was kept cool by contact with water.

Figure (1) shows the piping scheme. Sections of 4" extra heavy piping were used for the oil reservoir, which was proportioned to allow a two hours run. This reservoir was to be supported by a suitable prop resting on scales. It may be noted that the oil would have a slight static head besides the pressure of 250 pounds per square inch required in the entire pipe line. Considerable difficulty was encountered in attempting to maintain this pressure. The slightest leak would cause a drop. At first cylinder oil and graphite was used on the oil line and white lead on the air line to prevent leaky joints. These held at 100 pounds, but not at 250 pounds. Litharge and glycerine was finally used with good effect.

PISTON VALVE
USED FOR
OIL INJECTION
INTO
GAS ENGINE





A considerable amount of time was consumed in locating and remedying the small leaks which caused the annoying drop in pressure from the high value required. We were finally able to hold 300 pounds in the pipe line, provided the valves to the engine were not opened.

When the oil reservoir was filled, and sufficient pressure accumulated, the valves to the engine were opened. The small piston worked perfectly at every explosion, allowing oil and air to enter but NOT IN THE PROPER POINT IN THE STROKE.

The pressure in the line dropped immediately when the ports were uncovered. This resulted in the oil being forced back in the line till late in the expansion stroke, when it was sprayed into the cool gases. The same effect was produced as would take place if oil were poured into the intake pipe, i.e.. the heating value of the gas mixture was increased. This was shown by the more violent explosions. No other effect was noted on the indicator card! Diaphragms with small holes were placed in the unions with the object of holding the pressure. When they were small enough to hold up the pressure they would not allow sufficient oil or air to enter to produce noticeable results. The slightest egress for air caused a drop in pressure in the line sufficient to prohibit any results being obtained. If sufficient time had remained, this defect could have been remedied either by providing a large extra heavy air tank, or by substituting a new pump for the one used.

As our available time prohibited obtaining either of these, we were unable to determine the effect on the indicator card, crank effort, or efficiency, due to the oil injection at the proper point in the cycle. From the results of our experience, the following recommendations are made for future investigation along this line:-

1. Allow plenty of time to overcome unforseen difficulties. It is probable that one of these will be caused by imperfect combustion

of the oil with a result of clogged valves and grinding of the cylinder. This might be overcome by warming the oil and heating the air, allowing a large excess of the latter.

2. Select the second method of attack enumerated, i.e., positive feed of oil with a small specially constructed pump for oil, the piston of which is in connection with the main shaft in the proper intervals, these intervals being governed by either the inlet or exhaust valve.

It is with reluctance that we leave this most interesting and promising subject. If our efforts serve in a small way to stimulate further investigation along this line, we shall feel that our time has not been wasted.